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Precise measurement of Higgs decay rate into WW^* at future e$^+$e$^-$ Linear Colliders and theoretical consequences

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1   Introduction

Assuming a SM or MSSM scenario[1], one expects a light Higgs boson which could be studied in great detail with a LC operating at $\sqrt{s} > m_h + m_Z$. In the TESLA scenario, with 500 fb^{-1} accumulated at $\sqrt{s}$ =350GeV, about 10^5 hZ events could be produced through the Higgsstrahlung process.

At a future LC with a $\sim$ 1 cm beam-pipe radius and a thin Si detector there will be excellent separation between the various flavours[2]. With the high statistics available it will thus become possible to measure the various branching ratios with a few % error. Typically one expects 8 % precision on $BR(h \rightarrow \bar{c}c)$, 6 % on $BR(h \rightarrow gg)$ and $\sim$ 1% on $\sigma(hZ) \times BR(h \rightarrow \bar{b}b)$. Furthermore, if m$_h$ >100 GeV, one will be able to access to BR(h$\rightarrow WW^*$) and, as explained in section 3, this measurement can give access to the Higgs total decay width and therefore to all partial widths. In particular one can precisely measure $\Gamma(h \rightarrow \bar{b}b)$ and $\Gamma(h \rightarrow \tau^+\tau^-)$ which have a high sensitivity to MSSM effects[3] and therefore allow an essential test of the Higgs sector. If m$_A$ < 1 TeV, it becomes possible to measure a significant deviation and, within MSSM, to give an indirect estimate of m$_A$ thus extending the effective sensitivity above the discovery domain of LHC.

In the following section we describe a detailed analysis on the measurement of BR(h$\rightarrow WW^*$).

2   Measurement of the branching rate $h \rightarrow WW^*$

In this paper we study the possibility of selecting the decay $h \rightarrow WW^*$ for the mass of h in the range 110 - 140 GeV/c^2 with a linear e^+e^- collider at $\sqrt{s}$= 350 GeV and with an integrated luminosity of 500 fb^{-1}. The possibility to select this decay mode for a heavier Higgs boson is discussed elsewhere[4, 5].

Both signal and background processes were generated using PYTHIA [6] version 5.722 with the initial state radiation switched on. For the moment we did not take into account the beamstrahlung which gives additional $\sim$3% spread of the centre-of-mass energy and some tails. To simulate the detector response, we suppose the following parameters of the detector. The charged and neutral particles are registered if their momentum is more than 100 MeV/c and the polar angle of their direction is $|cos\theta|$ < 0.99. The efficiency of particle reconstruction is 99%. The transverse momentum resolution for the charged particles is: $\delta p_t/p_t^2 = 7. \times 10^{-5}(GeV/c)^{-1}$. The energy resolution for the photons is $\delta E/E = 0.10/\sqrt{E} \oplus 0.01$ and for the neutral hadrons is $\delta E/E = 0.50/\sqrt{E} \oplus 0.04$ (E is in GeV).

We consider the reconstruction of $h \rightarrow WW^*$ in the process $e^+e^- \rightarrow hZ$ with $WW^* \rightarrow l\nu q\bar{q}$ ($l = \mu, e$), $Z \rightarrow q\bar{q}$. This final state covers 20.4% of all decays of $(h \rightarrow WW^*)Z^0$. The measurement of this h decay in the other final states is also possible. The main sources of the background are the production of W^+W^-, Z^0Z^0 and $t\bar{t}$. The dominating h decay, $h \rightarrow b\bar{b}$, also gives some contribution to the background. We find that the contribution of $e^+e^- \rightarrow q\bar{q}$ when $q \neq t$ as well as that of other processes ($We\nu$, Zee etc.) can be reduced to the negligible level by the topological cuts.

The selection procedure starts by the selection of the lepton (electron or muon) with an energy above 10 GeV. The remaining particles are clustered into jets using the JADE algorithm with $y_{min} = 0.01$[6]. The events with the number of jets less than 3 are rejected.

The transverse momentum of the lepton with respect to the nearest jet is required to be greater than 8 GeV/c. The total visible mass of all particles excluding the lepton should be in the range: $130 < M_{vis} < \sqrt{s} - 40$ GeV/c^2 and the mass of the system "lepton-missing momentum" should exceed 10 GeV/c^2.

Some cuts are constructed to reduce the specific types of the background. To suppress the background from $ZZ^{(*)} \to l^+l^- q\bar{q}$ the event is removed if the mass of given lepton candidate with any other lepton is within the Z^0 mass ($|M_{ll} - M_Z| < 15$ GeV/c^2) or less than 15 GeV/c^2. Additionally we reject event if one of jets contains only one charged particle or have the mass less than 2 GeV/c^2.

The variable $\cos\theta_{vis} \times Q_l$, where θ_{vis} is defined as the polar angle of the direction of the visible momentum (excluding the lepton) and Q_l is the charge of the lepton, is required to be: $-0.95 < \cos\theta_{vis} \times Q_l < 0.90$. This cut reduces the background of W^+W^-, which is produced in the forward direction, and $ZZ^{(*)}$, which is produced both in the forward and backward directions.

The channel $e^+e^- \to W^+W^- \to l\nu q\bar{q}$ has initially 2 partons so that events with 3 or more jets can arise only from gluon emission. To suppress such events the variable sensitive to the gluon emission can be used. We use the variable $E_{min} \times \alpha_{min}$ where E_{min} is the minimal jet energy and α_{min} is the minimal angle between any two jets. This variable is widely used to suppress events with gluon emission in LEP experiments. Its distribution for W^+W^- and hZ events is shown in Fig.1. Certainly more sophisticated variables from the arsenal of the methods developed at LEP can give even better suppression of this type of background. We reject events if $E_{min} \times \alpha_{min} < 45$ (GeV×rad) for events with 3 jets and $E_{min} \times \alpha_{min} < 20$ (GeV×rad) for events with 4 and more jets. This variation for the different number of jets is explained by the fact that the remaining W^+W^- events are mainly 3-jet like, while hZ events are more 4-jet like.

Finally all particles in the event, excluding the lepton, are forced to 4 jets and for each possible pairing of jets the mass of the pair of jets and the recoil mass were computed. The distribution of the recoil mass when the mass of the pair is within 10 GeV/c^2 of the nominal Z^0 mass is shown in Fig.2 for the signal with $M_H = 120$ GeV/c^2 and for 3 dominant types of background. The normalisation in each case is arbitrary. We select the event if the mass of the pair $|M_{jj} - M_Z| < 10$ GeV/c^2 and the recoil mass $|M_{rec} - M_H - 5.0| < 15$ GeV/c^2. This cut gives very strong suppression of W^+W^- (20 times) and $t\bar{t}$ (> 200 times) background. The impact on the signal is also strong and more than 50% of the signal events are removed by this condition. This effect is explained by undetected ISR and by errors in the jet clustering and in the measurement of the energy flow. Some optimisation of the analysis is possible at this stage, however this cut should be kept in some form to reduce the background of $t\bar{t}$ to a reasonable level. Another alternative is to perform this measurement below the $t\bar{t}$ threshold. The remaining number of events for $\int L dt = 500$ fb^{-1} for the different types of background and for the signal is given in table 1.

It should be noted that ~100% of the remaining $t\bar{t}$, 85% of ZZ and 90% of $h \to X \neq WW^*$ background contains jets with B-hadrons while for the decay $h \to WW^*$ B-hadrons can only be produced in the decay $Z^0 \to b\bar{b}$ with $BR(Z^0 \to b\bar{b}) = 0.154$. This kind of background can therefore be effectively suppressed by applying the anti-b tagging. The precise vertex detector and the efficient b-tagging algorithms developed for experiments at LEP and SLC can provide background suppression by more than 20 times while keeping the efficiency for the signal at the 90-95% level. In this study we apply a "soft" anti-b tagging which removes the event if a B-hadron is found in the jets not included into the
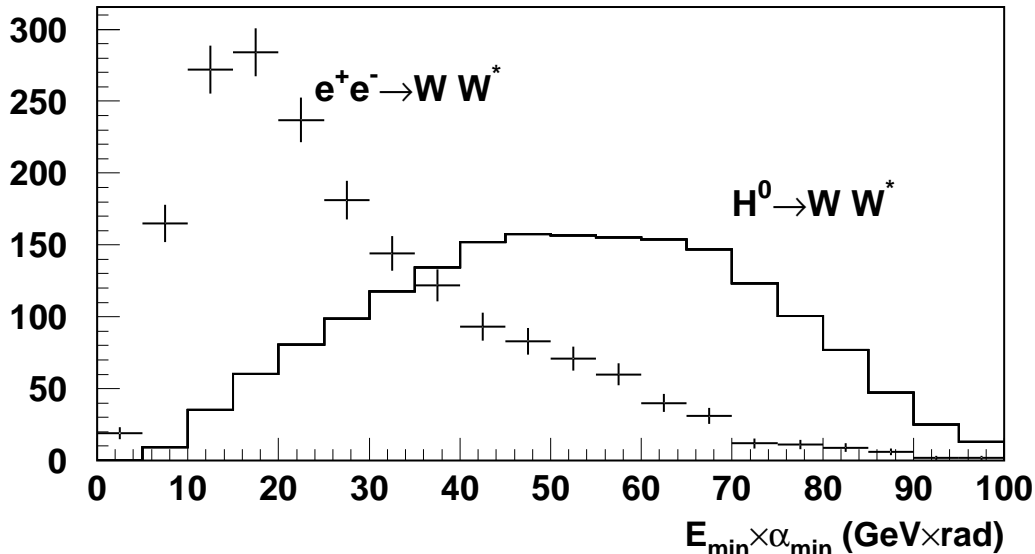
Figure 1: Distributions of $E_{min} \times \alpha_{min}$ for the signal (histogram) and for the WW background (points) with the arbitrary normalisations.

"Z^0-like" pair. We suppose that the efficiency of anti-b tagging is 5% for an event with 2 B-hadrons and 95% for the event without B-hadron. The number of events remaining after this selection is given in table 2 and figure 3 shows the distribution of the recoil mass for M_H=120 GeV/c^2.

The only important background which remains after above selections is the production of WW^* pairs when one of W is off-shell. There is an interesting possibility to additionally reduce the WW^* background using a polarised e^- beam. For the right-handed incoming electron with polarisation P_{e^-} the cros-section for WW production is suppressed approximately by a factor $1 - P_{e^-}$ while the cros-section of the h production is almost unchanged. Therefore an electron polarisation $P_{e^-} \sim 0.90$ is sufficient to suppress WW^* background and obtain the pure sample of $h \rightarrow WW^*$ decays.

There are several ways to improve the precision of the measurement of $BR(h \rightarrow WW^*)$. We note that the present analysis covers only 20% of the $Z^0 H \rightarrow WW^*$ decay modes. With the level of background reachable with polarisation, one can probably access to the hadronic W decay modes and/or to $Z^0 \rightarrow \nu\bar\nu$ etc... Therefore an increase of the efficiency by a factor ~ 2 seems feasible. We also note that the selection efficiency drops by 50% due to our cut on the recoil mass which could be avoided by working below the $t\bar t$ threshold. Thus we can expect that the statistical errors given in table 2 could be reduced by about a factor 2 if necessary. We also expect that the measurement of this decay mode with $\sim$10% precision for the Higgs boson with the mass around 100 GeV/c^2 could be possible in an experiment below $t\bar t$ threshold with a polarised beam.

M_H	BR(WW)	$H \to WW$	$H \to X \neq WW$	WW	ZZ	$t\bar{t}$	$(\delta(Br)_{stat}/Br)(\%)$
110	0.05	152	49	46	71	26	12.2
120	0.14	535	58	116	61	72	5.4
130	0.30	1280	44	267	55	175	3.3
140	0.48	2148	42	371	54	368	2.5

Table 1: Number of selected events for the different processes. The last column gives the expected statistical precision of the measurement for $\int Ldt = 500$ fb^{-1}.

M_H	BR(WW)	$H \to WW$	$H \to X \neq WW$	WW	ZZ	$t\bar{t}$	$(\delta(Br)_{stat}/Br)(\%)$
110	0.05	143	3	43	18	7	10.2
120	0.14	503	4	109	17	20	5.1
130	0.30	1203	5	251	17	45	3.2
140	0.48	2019	5	349	15	99	2.5

Table 2: Number of selected events after applying an anti-b tagging selection. The last column gives the expected statistical precision of the measurement for $\int Ldt = 500$ fb^{-1}.

3 Theoretical Implications

The minimal SUSY scenario MSSM, with two Higgs doublets, predicts two CP-even Higgs bosons h and H with a mixing angle α, one CP-odd boson A and two charged bosons H$^{\pm}$. MSSM predicts m$_h$ <130 GeV, while no clear upper bound is given for the rest of the spectrum. In the mSUGRA and gauge-mediated scenarios one generally expects that these particles will be heavy[7] and therefore not directly observable at the first stage of a LC operating at $\sqrt{s}$ <500 GeV. In the appendix, we recall why $\Gamma(h \to \bar{b}b)$ has a high sensitivity to MSSM provided m$_A$ <1 TeV. This quantity cannot be directly measured but requires a combination of at least two measurements. As discussed below, a precise measurement is only feasible if the channel h$\to WW^*$ is experimentally accessible. This is possible when m$_h$ > 100 GeV, a scenario becoming increasingly probable with the LEP2 limits reaching 95 GeV. Nevertheless, for the sake of comparison, two scenarios will be discussed.

1/ BR(WW^*) not accessible

One can measure σ(hZ) inclusively (using the Z leptonic decays) with the precision $\sim$2% and σ(hZ)BR(h$\to \bar{b}b$). BR(h$\to \bar{b}b$) has some sensitivity to m$_A$, but this sensitivity is reduced with respect to $\Gamma(h \to \bar{b}b)$ since the total width itself is dominated by the same contribution and since the extra contributions to the total width coming from $\Gamma(h \to \bar{c}c)$ and $\Gamma(h \to gg)$ are not accurately computable.

BR(h$\to \bar{b}b$)/BR(h$\to \bar{c}c$) is also accurately measurable and, as shown in the appendix, has the same sensitivity to MSSM as $\Gamma(h \to \bar{b}b)$. It turns out however that $\Gamma(h \to \bar{c}c) \sim m_c^2(m_h)$ is poorly known at the theoretical level. This translates into an uncertainty on $\Gamma(h \to \bar{c}c)$ of at least 10% which reduces the sensitivity on m$_A$ to $\sim$ 500 GeV.

One can alternatively access to the total decay width Γ_T and then derive $\Gamma(h \to \bar{b}b)$=BR(h$\to \bar{b}b$)Γ_T. To do this, one uses $\Gamma(h \to \gamma\gamma)$ measured with a $\gamma - \gamma$ collider and

| m_h | BR($WW*$) | bb/WW^* | Γ_T | 95 % C.L. m_A |
GeV	%	%	%	GeV
110	5	10	10	550
120	14	5	5	750
130	30	3	3.6	1000
140	48	2.5	3.2	1100

Table 3: Typical precision for Higgs branching ratios with 500 fb^{-1} at 350 GeV

BR(h$\to \gamma\gamma$) measured in e$^+$e$^-$. Recent[8] estimates however predict a statistical accuracy on BR(h$\to \gamma\gamma$) not better than 15 %.

In conclusion this scenario, even with the TESLA luminosity, does not allow to reach an accuracy better than 10 % on $\Gamma(h \to \bar{b}b)$.

2/ BR(WW^*) accessible

In this scenario one can directly measure Γ(h$\to \bar{b}b$)/Γ(h$\to WW^*$) which, as shown in the appendix, has the same sensitivity to m_A as $\Gamma(h \to \bar{b}b)$. This simple minded statement assumes MSSM in which the Higgs boson has a SM-like coupling to vector bosons. This assumption can however be tested in two complementary ways. One can test the h-Z-Z coupling via the measurement of the Higgsstrahlung cross-section $\sigma(Z^* \to hZ)$ and assume universality with the h-W-W coupling. The latter assumption can be checked by measuring the fusion process e$^+$e$^- \to \nu\bar{\nu}W^*W^* \to$h which allows to accurately verify universality.

After performing these checks, if no deviation is observed on the h-W-W coupling, one can safely compare Γ(h$\to \bar{b}b$)/Γ(h$\to WW^*$) to the MSSM predictions and derive a limit on m_A. Table 3 indicates the type of accuracy which can be reached for 4 Higgs masses. As noted previous section a dedicated measurement performed below the top threshold could allow an improved statistical accuracy by about a factor 2.

Figure 4 indicates the corresponding sensitivity which can be reached on m_A. In a favourable case, say m_h=120 GeV, the statistical accuracy is sufficient up to $m_A \sim 1$ TeV.

This sensitivity can be compared to the LHC discovery reach. Direct observation of a heavy A is only possible at low $tan\beta$ (region excluded if no Higgs is found with mass below 100 GeV) or very high $tan\beta$ through the decay of A into $\tau^+\tau^-$. This leaves a large interval which a precise measurement of Γ(h$\to \bar{b}b$) would allow to cover.

At this stage one should take into account the various systematical errors. On the theoretical side, the most obvious effect comes from the uncertainty on the b quark mass. At present the error is $> 1\%$ and therefore this effect can be relevant. A possible way out is to use the measurement of Γ(h$\to \tau^+\tau^-$) for which the statistical error will probably be worse. On the experimental side, one should note that at LEP2 the typical efficiency on the $\tau^+\tau^-$ channel is about 20 % but this comes from the limited vertex accuracy of LEP2 detectors which are unable to detect vertex offsets from τ particles while this would not be the case at future LC.

Another source of uncertainty comes from theoretical inputs, like for instance the radiative corrections. As discussed in the appendix, it seems that the dependence on unknown parameters is weak provided that $tan\beta$ is above 2 (or equivalently that m_h is above 100 GeV). This statement is probably too naive and deserves further investigations.

Finally, if no deviation is observed on the h-W-W to coupling, one can also access

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to the total Higgs decay width using $\Gamma_T = \Gamma(WW^*)/BR(WW^*)$, where $\Gamma(WW^*)$ is a computable quantity and $BR(WW^*)$ is obtained from the measurements of $\sigma(hZ) \times BR(WW^*)$ and $\sigma(hZ)$. The total Higgs decay width could therefore be measured with a much higher precision than by using the $\gamma - \gamma$ channel. The numbers given in table 3 assume the error on $\sigma(hZ)$ of 2%.

4   Conclusion

A precise measurement of BR(h$\to WW^*$), possible if m$_h$ >100 GeV, allows to measure precisely the Higgs total decay width and therefore access to $\Gamma(h \to \bar{b}b)$. This extends considerably our ability to discriminate between the SM and MSSM scenario and therefore illustrates the potential of precise measurements of Higgs branching ratios.

Appendix

The following calculations give a simplified treatment only meant to understand the dependence of various observables in terms of the MSSM parameters.

One has $\Gamma(h \to \bar{b}b) = \Gamma_{SM}(h \to \bar{b}b)sin^2\alpha/cos^2\beta$ where α, varying between $-\pi/2$ and 0, defines the mixing between the two CP-even Higgs bosons and β, varying between $\pi/4$ and $\pi/2$, is defined from the ratio of the vacuum expectations of the two doublets.

This two angles are related through the formula :

$$tan2\alpha = tan2\beta\frac{m_A^2 + m_Z^2}{m_A^2 - m_Z^2 + \epsilon/cos2\beta}$$

with :

$$\epsilon = \frac{3G_F}{\sqrt{2}\pi^2}\frac{m_t^4}{sin^2\beta}Log(m_{\tilde{t}_1}m_{\tilde{t}_2}/m_t^2)$$

where $m_{\tilde{t}_{1,2}}$ are the two stop masses.

This is an approximate formula, ignoring mixing effects, but good enough to get a first guess of the relevant effect.

When m$_A >> m_Z$, this formula shows that $\beta - \alpha \to \pi/2 - \eta$ where η is small. One can easily derive that :

$$\eta = \frac{m_Z^2|cos2\beta| + \epsilon/2}{m_A^2 - \epsilon/|cos2\beta|}sin2\beta$$

One has :

$$\frac{sin^2\alpha}{cos^2\beta} \to 1 - 2\eta tan\beta$$

Similarly one can estimate the change on the hZ cross-section :

$$sin^2(\beta - \alpha) \to 1 - \eta^2$$

From this one concludes that there is a linear dependence on η for the width while the cross-section has a quadratic dependence therefore vanishing quickly for large m$_A$.

Figure 4 shows the behaviour of $\Gamma(h \to \bar{b}b)/\Gamma(h \to WW^*)$. One observes the same behaviour as in [3]. The region at low $tan\beta$ is cut away by requesting that the MSSM parameters are compatible with a Higgs mass of 110 GeV.

Note that $\Gamma(h \to \tau^+\tau^-)$ has the same correction factor than $\Gamma(h \to \bar{b}b)$.

For what concerns $\Gamma(h \to \bar{c}c)$, the correction factor :

$$\frac{cos^2\alpha}{sin^2\beta} \to 1 + 2\eta/tan\beta$$

This expression allows to understand why the effect coming from $\Gamma(h \to \bar{c}c)$ is reduced : since $\eta=0$ for $tan\beta=1$, this effect is only relevant for larger values of $tan\beta$ but then it is damped with respect to the corresponding effect on $\Gamma(h \to \bar{b}b)$.

Figure 5 shows the behaviour of $\Gamma(h \to \bar{b}b)/\Gamma(h \to \bar{c}c)$.

For large m_A, the Higgs mass is given by :

$$m_h^2 = m_Z^2 cos^2 2\beta + \epsilon sin^2\beta$$

One can therefore express the term $\eta tan\beta$, which defines the correction effect for $\Gamma(h \to \bar{b}b)$, in terms of m_h^2 :

$$\eta tan\beta = -\frac{m_Z^2|cos2\beta| + m_h^2}{m_A^2 - \epsilon/|cos2\beta|}$$

If we assume that $tan\beta > 2$ and that m_A is large, one can drop the $cos2\beta$ dependence with no significant loss of precision:

$$\eta tan\beta = -\frac{m_Z^2 + m_h^2}{m_A^2}$$

meaning that the correction factor is essentially independent of $tan\beta$, as can be inferred by the curves of figure 4. Present LEP2 limits, within some assumptions, tend to exclude the low $tan\beta$ region and it seems therefore that this approximation will apply.

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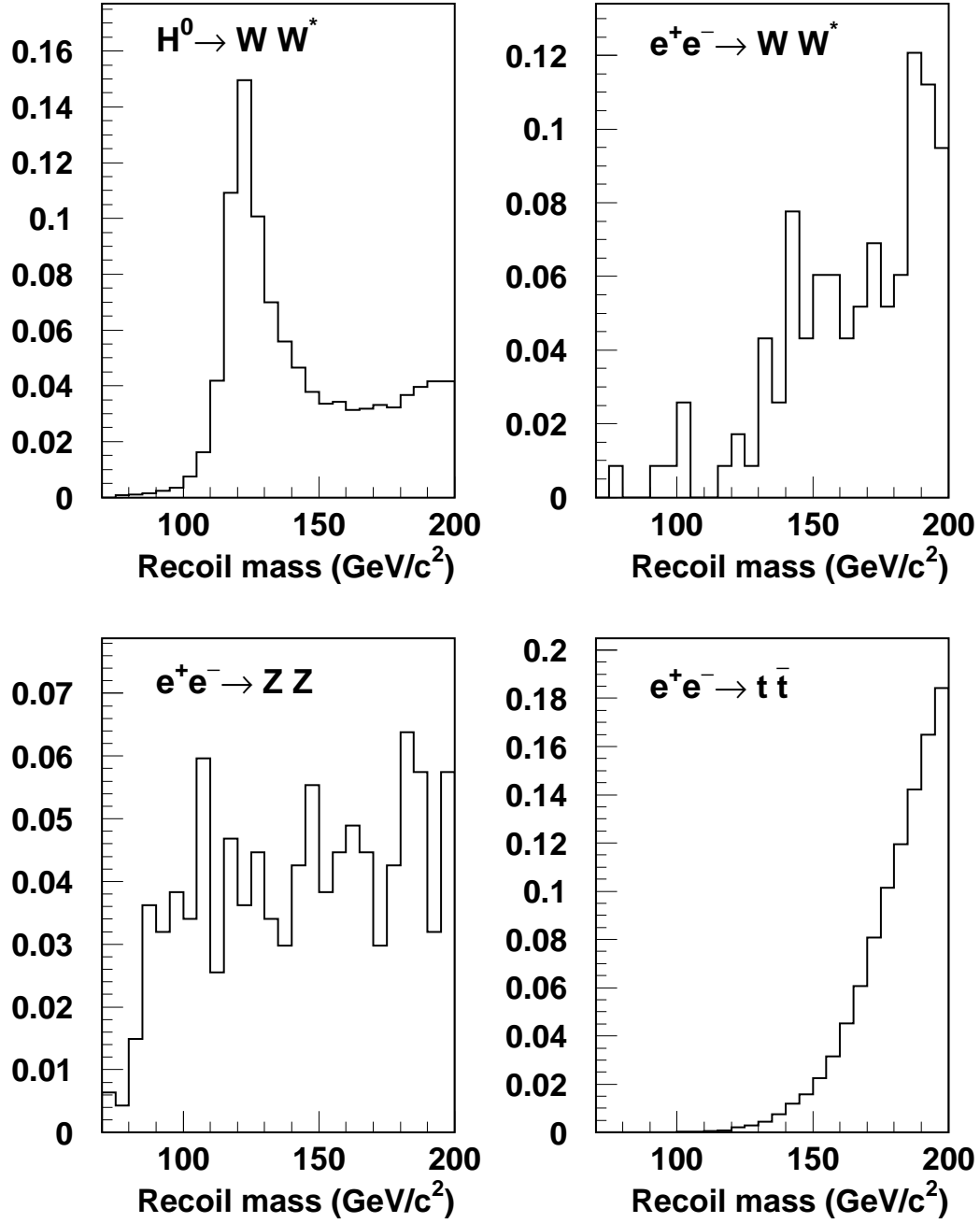[8] J.C. Brient, The Higgs decay in 2 photons, ECFA/DESY working group.

Figure 2: Distributions of the recoil mass for the signal with $M_H = 120$ GeV/c^2 and for the main types of background. The normalisation is arbitrary.
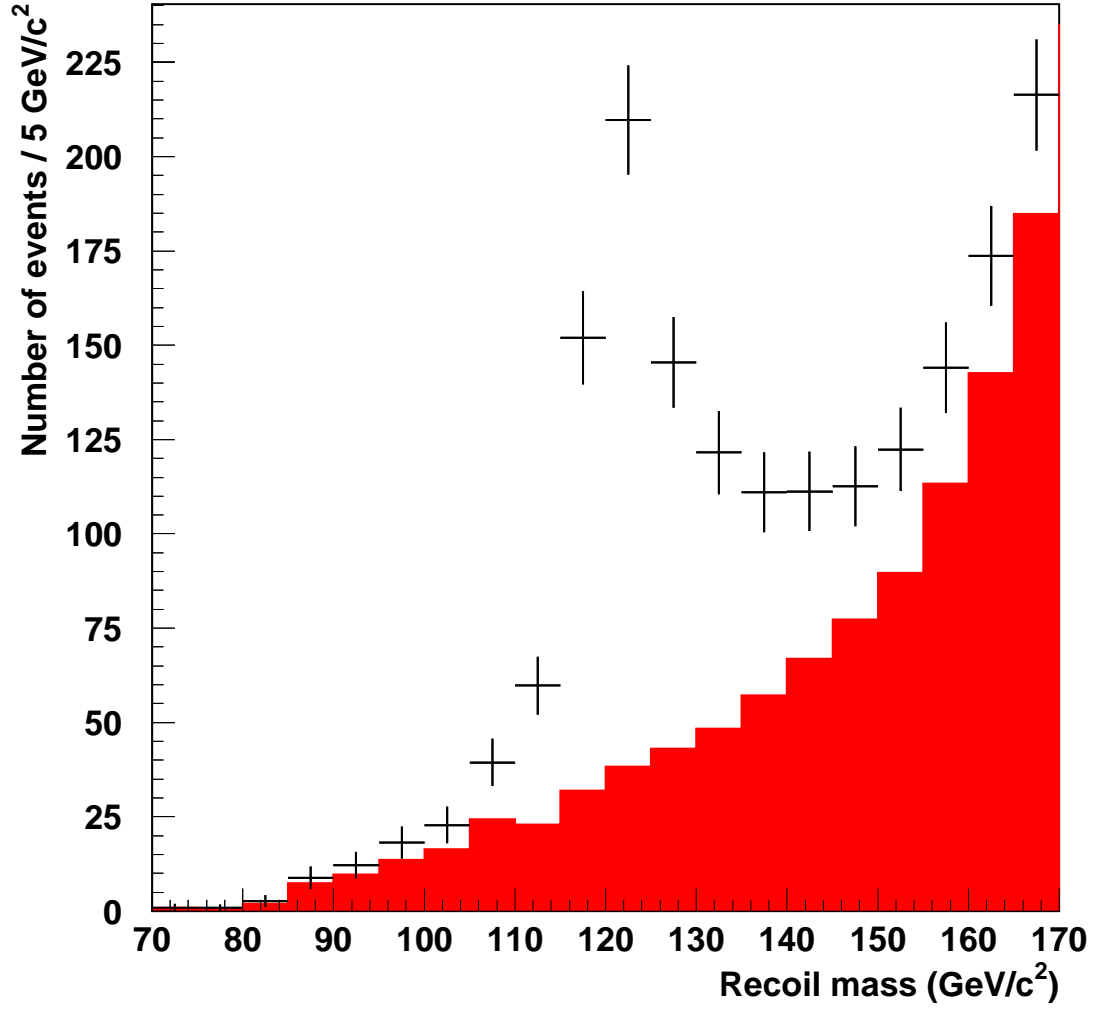
Figure 3: Expected distributions of the mass recoiling to any pair of jets with $|M_{jj} - M_Z| < 10$ GeV/c^2. The distribution is normalised to $\int L dt = 500$ fb^{-1}. The filled histogram shows the mass distribution for the background. The signal $h \rightarrow WW^*$ is generated with $M_H = 120$ GeV/c^2.
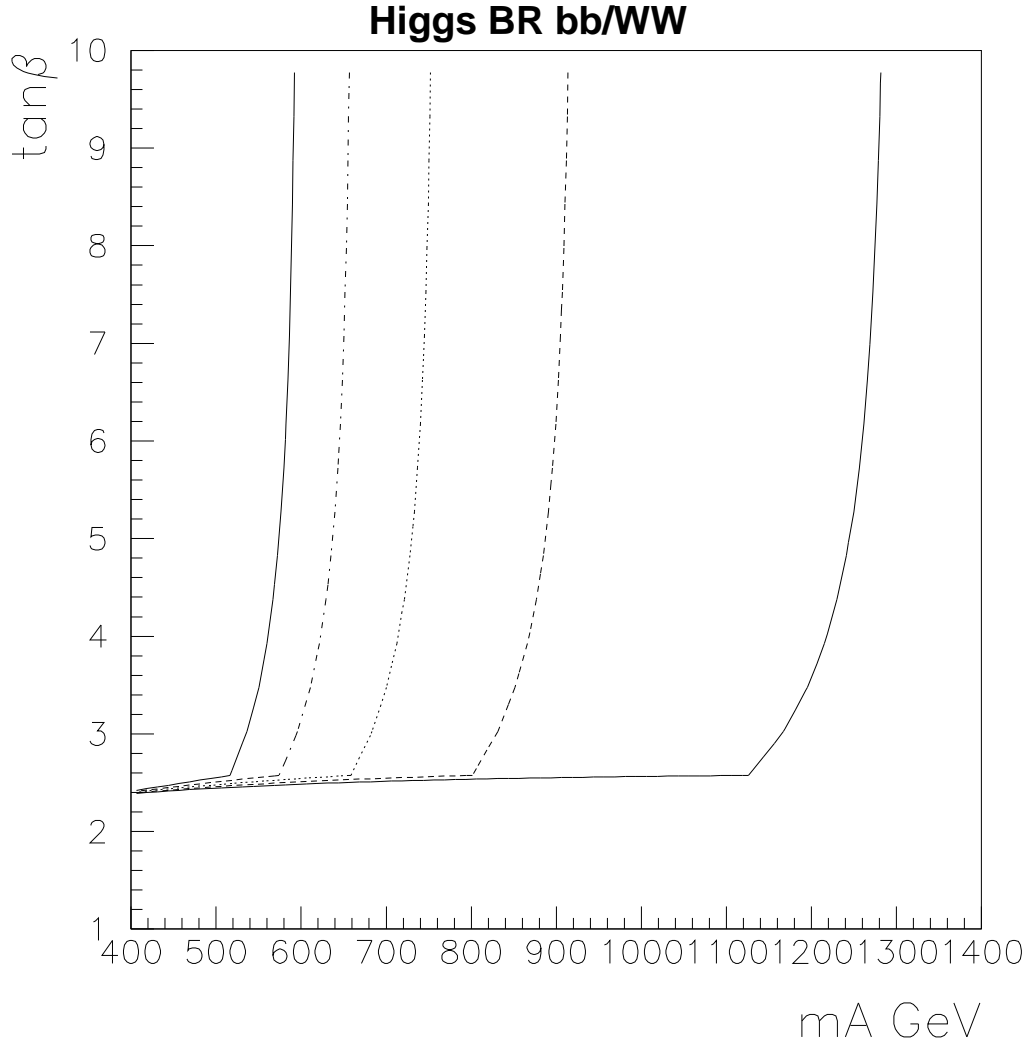
Higgs BR bb/WW

Figure 4: MSSM effect on BR(h$\to b\bar{b}$)/BR(h$\to WW^*$) for m$_h$=110 GeV. The 5 curves correspond to 1.03,1.06,1.09,1.12 and 1.15 correction factors.
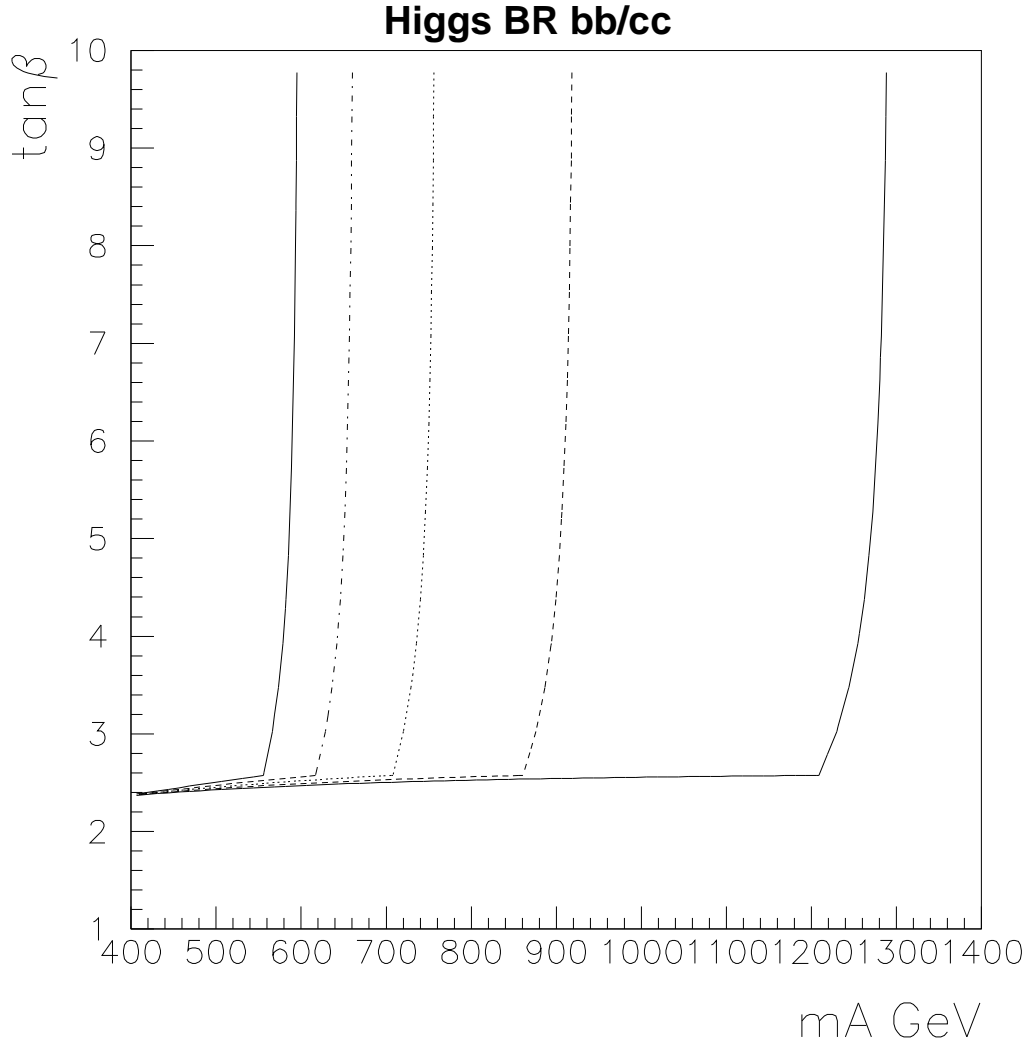
Figure 5: MSSM effect on BR(h→ $b\bar{b}$)/BR(h→ $c\bar{c}$) for m$_h$=110 GeV. The 5 curves correspond to 1.03,1.06,1.09,1.12 and 1.15 correction factors.